AEDC-TR-68-36

OBSERVATIONS ON THE INFLUENCE OF AMBIENT PRESSURE ON BOUNDARY-LAYER TRANSITION

J. Leith Potter
ARO, Inc.

March 1968

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NOTICES

OBSERVATIONS ON THE INFLUENCE OF AMBIENT PRESSURE ON BOUNDARY-LAYER TRANSITION

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FOREWORD

The research reported herein was done at the request of the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), under Program Element 6240533F, Project 8953,' Task 895309.

The results of tests presented were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of AEDC, AFSC, Arnold Air Force Station, Tennessee, under Contract AF40(600)-1200. The experiments were conducted between March 1 and October 31, 1967, under ARO Project Nos. VT5812 and VT2727, and the manuscript was submitted for publication on January 17, 1968.

Out of consideration of the human element involved in reading the photographic data, the author asked two colleagues to furnish independent readings of wetted length to transition to add to his own. For this kindness he owes K. E. Koch and J. D. Whitfield his thanks.

This technical report has been reviewed and is approved.

Carl E. Simmons Captain, USAF Research Division Directorate of Plans and Technology	Edward R. Feicht Colonel, USAF Director of Plans and Technology

ABSTRACT

For at least 15 yr it has been known that the Reynolds number characterizing transition from laminar to turbulent boundary-layer flow (based on local properties and wetted length to transition) may be influenced by the local unit Reynolds number $(U/\nu)_\delta$ or some still unidentified, related quantity under both subsonic and supersonic conditions. Because examples of this were available almost exclusively from wind tunnel work, and because of the possibility that free-stream disturbances were responsible, there has been uncertainty as to whether the so-called unit Reynolds number effect exists in atmospheric free flight. The study described here was conducted in a free-flight range, thereby circumventing "wind tunnel effects," and it has resulted in a demonstration of the variation of transition Reynolds number with range pressure (or unit Reynolds number) under conditions of fixed Mach number and average wall temperature ratio. Some preliminary measurements of sound pressures in the range air are reported for comparison with published results for wind tunnels.

CONTENTS

ILLUSTRATIONS

TABLE

NOMENCLATURE

C_{D_o}	Total drag coefficient at zero angle of attack
M_δ	Cone surface Mach number based on inviscid perfect gas
M_∞	Free-stream Mach number
$\tilde{p}$	Pressure fluctuation in ambient air
p_∞	Ambient pressure
$Re_{\delta,t}$	Reynolds number based on cone surface conditions, assuming inviscid perfect gas, and wetted length to transition
$Re_{\infty,x}$	Reynolds number based on free-stream properties and wetted cone length
T_{aw}	Computed cone surface adiabatic recovery temperature for laminar flow
T_w	Average surface temperature
T_∞	Ambient temperature
$(U/\nu)_\delta$	Unit Reynolds number based on inviscid, perfect gas cone surface conditions
$(U/\nu)_\infty$	Unit Reynolds number based on free-stream conditions
X_t	Transition location, based on wetted length
γ	Ratio of specific heats

SECTION I
INTRODUCTION

Although wind tunnels have been widely and effectively used for studies of boundary-layer transition, there exists convincing evidence that the so-called "tunnel effects," notably free-stream turbulence or noise, may sometimes affect the transition process to a degree causing uncertainty in investigations of other more easily isolated factors influencing transition. Therefore, even after it had been established that changes in the local unit Reynolds number, $(U/\nu)_\delta$, or some yet unidentified, related parameter very often affect the local Reynolds number of transition, $Re_{\delta,t}$ (cf. Brinich, Ref. 1, Potter and Whitfield, Ref. 2, Laufer, Ref. 3, or Potter, Ref. 4), some doubt concerning the generality of this phenomenon remained. This is largely because of its demonstrated interrelation with the noise generated by the test section wall boundary layers of wind tunnels (cf. Laufer, Ref. 5, and Pate and Schueler, Ref. 6). Although a relatively few investigators have reported no U/ν effect in their work, the phenomenon is too thoroughly documented to doubt that it may occur in wind tunnels and must be accounted for in any transition-sensitive case. Clearly, free-flight range studies should shed much light on this question, but the limited amount of such data existing previously has not been adequate to convincingly establish that $(U/\nu)_\delta$ affects range results on $Re_{\delta,t}$.

Although the term "unit Reynolds number" is used, the writer hastens to point out that neither now nor previously has there been any insistence that this particular parameter is, per se, the complete or the most appropriate parameter. Obviously, drawing on training in dimensional analysis, it is tempting to suggest that some length will be found to combine with U/ν and make everything comfortably dimensionless again. This report does not clarify this puzzling problem; it only reports a gross observation, but it is one of some significance because it apparently establishes this phenomenon as more than a bothersome wind tunnel deficiency.

Using the data collected by W. R. Witt, who was studying spin-stabilized cone-cylinders in an aeroballistic range, Potter (Ref. 4) showed that transition Reynolds number increased markedly as range pressure and therefore $(U/\nu)_\delta$ increased. However, this avenue of investigation was not followed, and to the extent of the writer's knowledge, no other systematic range data bearing on this matter were published. Sheetz (Ref. 7) presented results for sharp, statically stable cones. These were launched without spin, and transition occurred in the absence of the pressure gradients present on the cone-cylinders referred to above.

However, because the later investigation was largely devoted to study of effects of average wall-to-adiabatic recovery temperature ratio, T_w/T_{aw}, on $Re_{\delta,t}$, the data are not adequate to permit a conclusion relative to the U/ν effect.

It was decided to conduct a series of launches of sharp, right circular cones in the Armament Test Cell, Hyperballistic (K) of VKF to determine how $Re_{\delta,t}$ would vary with $(U/\nu)_\delta$ at constant local Mach number, M_δ, and T_w/T_{aw}. In this case, as usual, $(U/\nu)_\delta$ was to be varied by adjusting range ambient pressure, p_∞, but the term unit Reynolds number or U/ν is used in the subsequent discussion since it is believed to be the more basic though not necessarily the complete factor, following the work of Brinich (Ref. 8). Furthermore, because of the concern over the role of noise generated by the test section wall boundary layer in connection with the U/ν effect demonstrated in wind tunnels, an exploratory effort was made to evaluate the noise present in the range at the time the cone passed the shadowgraph station where the location of transition on the cone was to be determined.

SECTION II
CONDITIONS OF EXPERIMENT

To aid the accuracy of reading shadowgraphs and to avoid ablation, cone semiangle, diameter, and free-stream Mach number, M_∞, were selected as 10 deg, 1.75 in. (4.445 cm)*, and 5, respectively. The 10-deg semiangle causes local unit Reynolds number to be appreciably higher than its free-stream value, and at $M_\infty = 5.08$, the actual average Mach number in this work, the bow shock wave is sufficiently removed from the cone surface to permit a clear view of the boundary layer. Further, at this Mach number and the corresponding flight speed of approximately 5730 ft/sec (1.75 km/sec) with an ambient temperature near 297°K, theoretically no ablation occurred on the 7075-T6 aluminum-alloy cones used for this experiment. Flight time from launcher muzzle to shadowgraph station was approximately 8.6 msec.

Under these conditions, including the short flight time, the average wall temperature, T_w, remains near 300°K, whereas the adiabatic

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*At the end of the program, one otherwise identical cone of 2.3-in. diameter was launched to broaden the feasible U/ν coverage.

recovery temperature, T_{aw} is around 1610°K, i. e., $T_w/T_{aw} \approx 0.184$. This rather low temperature ratio and the higher free-stream temperature, of course, set the range conditions apart from most wind tunnel cases, placing these results in the cold-wall category where several cases of transition reversal, re-reversal, and no reversal have been reported, cf. Refs. 9 through 12. Both the heat-transfer condition and the higher boundary-layer temperatures are particularly to be noted, inasmuch as these make quantitative comparison of these data with any others not duplicating the present conditions doubly hazardous.

Nose radius of the cones was 0.005 in. (0.127 mm). The influence of nose bluntness has been studied most recently by Stetson and Rushton (Ref. 12), in whose paper it may be seen that the present cones were "sharp" in the aerodynamic sense, i. e., local inviscid flow conditions may be based on theory for sharp cones.

The first few cones for these experiments had noses of copper alloy, and even though no surface discontinuity could be felt by hand before launch or seen in shadowgrams after launch, it was noticed that a weak shock wave always emanated from the joint between the copper and aluminum materials. Thus, the design was changed to eliminate the joint, and all data presented herein, except for a few specifically identified points, are traceable to the cones having no surface joints. Surface finish was around 10 microinches (μin.) or 0.25 μ rms, measured by use of a profilometer having a stylus tip radius of 500 μin. Thus, the reading must be regarded as qualitative, like similar data given in other reports on this subject.

Because of frequent cleaning of the interior of the range and long settling times (varying from 20 min to 20 hr), it seems unlikely that dust or range air turbulence could have produced any systematic effect in the data. In fact the range atmosphere probably was much cleaner than the airstreams of typical supersonic wind tunnels.

The instrumentation used to gain knowledge of the noise and its propagation consisted of a Bruel and Kjaer® 0.25-in. microphone system in combination with a Consolidated Electrodynamics Corporation® data tape system. The following values include any effects attributable to the latter:

Dynamic range:	70 to 174 db, peak (= 6.7×10^{-4} to 106 mm Hg, peak) (ref. to 1.5×10^{-7} mm Hg)
Limiting sound pressure:	185 db (= 224 mm Hg)
Response:	±3 db from 40 Hz to 80 kHz at 760 mm Hg and 25°C, ±3 db from 40 Hz to 40 kHz at 200 mm Hg and 25°C (ref. to output at 250 Hz)

The shadowgraph system incorporated a light source having a spark duration of 0. 15 μsec. Actually, this was a schlieren system modified to perform as a parallel-light shadowgraph system.

SECTION III
RESULTS

3.1 BOUNDARY-LAYER TRANSITION

In cases where transition is to be determined from the study of photographs, it is useful to present a figure illustrating the author's definition of the transition point which, of course, is not a point but a region often of considerable extent. This is accomplished in Fig. 1, where readers will note that the markers are placed where the author believes the boundary layer has become "finally" turbulent.

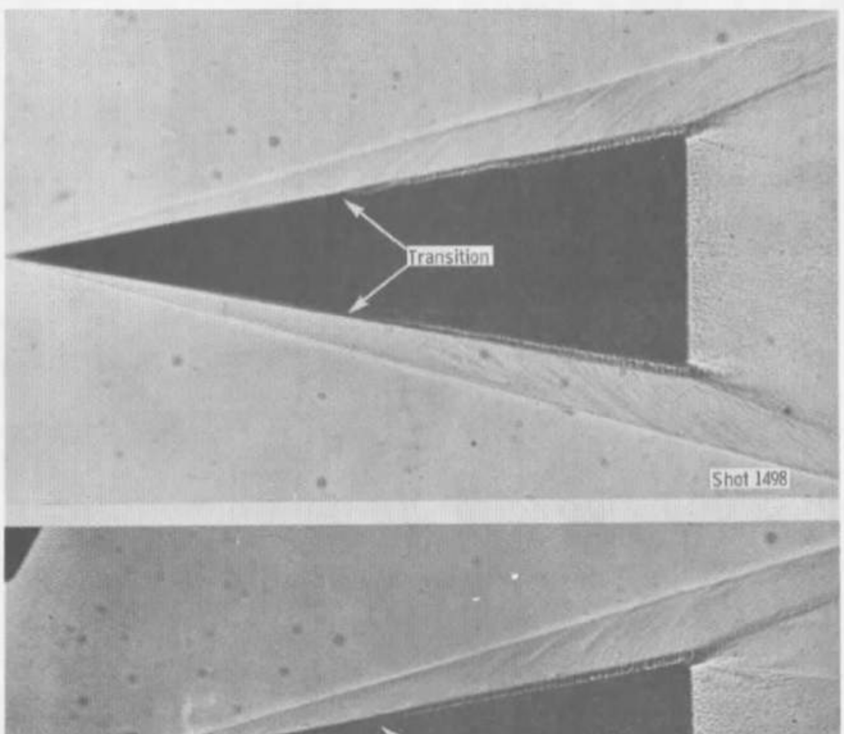

Fig. 1 Examples of Parallel-Light Shadowgrams and Definition of Transition

shadowgraph

This station was sometimes preceded by regions of turbulence alternating in streamwise order with areas of laminar flow, as seen in Fig. 1 (shot 1481), but the boundary layers remained turbulent downstream of the transition points given herein. As noted in Ref. 13, such stations generally lie near the middle of the transition region, being somewhat upstream of stations where surface impact pressure or heating rate distributions attain maxima. In the present case, data shown later imply that stations near the beginning of transition have been selected.

The maximum discrepancy between the lengths x_t read independently by the three individuals acknowledged in the Foreword and that read by any one of the group was 9 percent, and the average was 4.6 percent. The average of the three readings was used, and the results are presented in Table I and Fig. 2.

TABLE I
RESULTS FROM SHADOWGRAM READINGS

Shot Number	Range Pressure, mm Hg	Total Angle of Attack, deg	Angle of Attack in Photograph Plane	$(U/\nu)_\delta \times 10^{-6}$, in.$^{-1}$	M_δ	$Re_{\delta,t} \times 10^{-6}$
1475 ①	731.50	1.8 deg	1.8	3.54	4.25	9.76
1479	730.90	2.8	1.3	3.84	4.15	9.60
1481	547.80	1.0	0.8	3.10	4.65	8.74
1482	448.90	2.2	0.9	2.48	4.22	7.63
1483	350.10	3.2	1.1	2.05	4.37	6.61
1485	200.90	0.7	0.7	1.22	4.50	5.09
1486	200.00	1.2	0.6	1.23	4.50	4.41
1498	349.22	0.2	0.2	2.01	4.37	5.19
1620	299.85	1.4	0.7	1.66	4.24	4.80
1621	300.26	1.1	0.7	1.71	4.38	7.03
1623	525.44	2.7	0.0	2.96	4.30	7.16
1624 ②	125.54	1.4	0.4	0.664	4.15	3.11
1637 ①	735.00	3.2	3.0	4.26	4.38	9.19
1638 ③	736.40	2.8	2.8	3.66	4.10	8.60

① Copper nose with joint
② 2.3-in. diameter; all others 1.75-in. diameter
③ Steel throughout; no joint

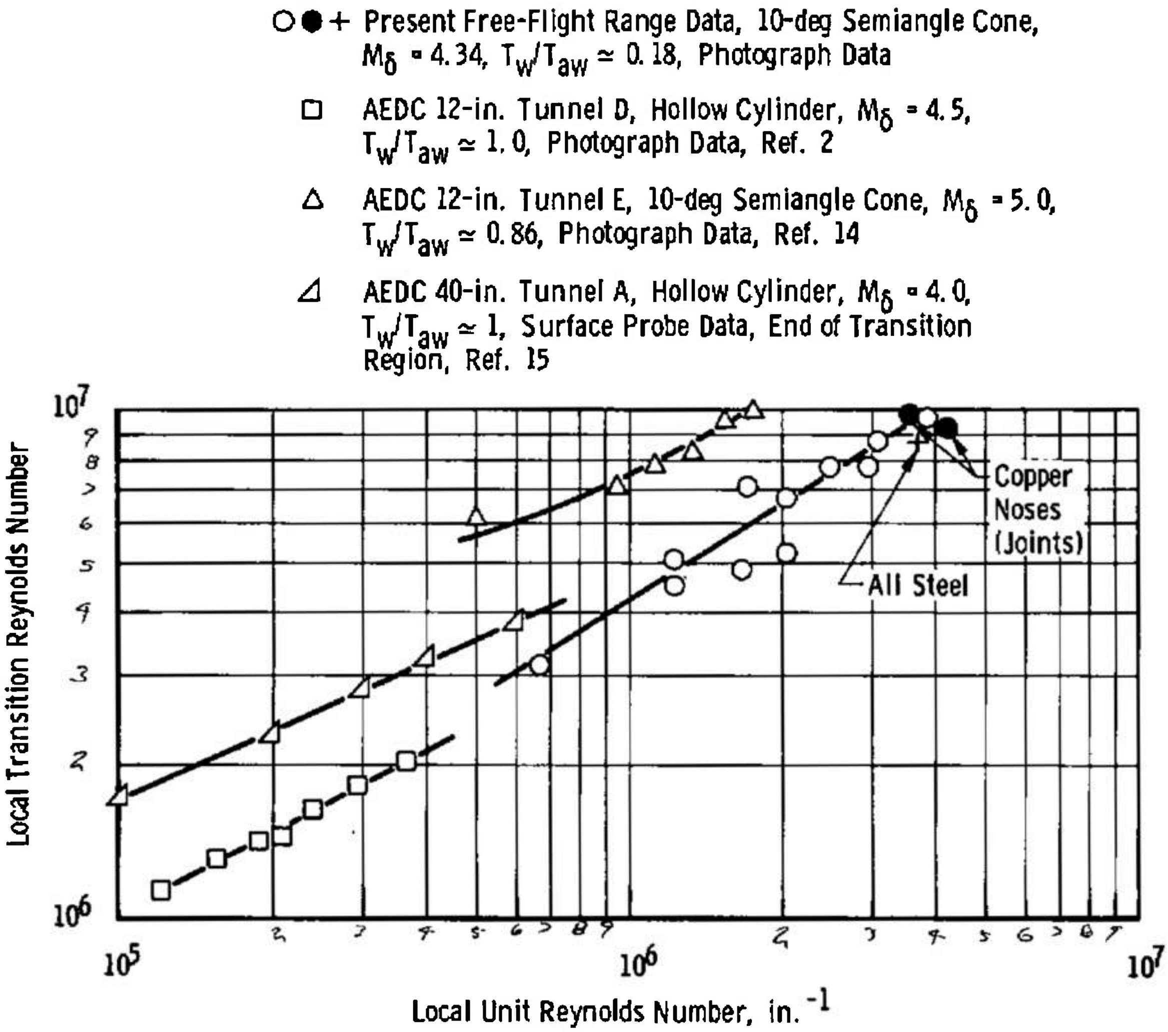

Fig. 2 Evidence of the Unit Reynolds Number Effect in an Aerophysics Range

Angles of attack assumed by the cones were always less than 3.2 deg in total, absolute value and averaged 1.8 deg. Also significant are the angles of attack in the plane of the photographs used to locate transition, the maximum in this case being 3 deg and the average 1.1 deg. Referring to Stetson and Rushton, it is reasonable to assume that $Re_{\delta,t}$ based on averaging the windward and leeward meridian readings was never more than 14 percent less than the "true" value for the total angles of attack experienced by these cones. For eight of the 14 data points this correction would be less than 5 percent on the same basis. Therefore, the points presented in Fig. 2 are windward and leeward, averaged, as read, with no adjustments.

In the few cases where it was desirable in order to permit reading transition locations on cones at lower angles of attack than existed at the

schlieren station, even though picture quality was not as good, x_t values were read from shadowgrams obtained at other range stations during the same launch. This was done on shots 1479, 1485, 1620, and 1623. Actually, $Re_{\delta,t}$ values differed very little on a given shot, even though total angle of attack varied up to 2 deg between the range stations compared. Presumably this reflects the uncertainty in interpreting the photographs, which is also, no doubt, the source of some of the experimental scatter in Fig. 2. It also should be expected because the angle of attack in the plane of the picture was seldom as great as the total angle; thus one would not expect to see as much effect of angle of attack as would be found if total (maximum) angle occurred in the plane of the photograph. For this reason, an assessment of the possible influence of finite angle in the present case is an inexact process, but a reasonable approach would seem to be the assigning of maximum leeward-to-windward transition location error bars based on the measurements of Stetson and Rushton. The results of this are shown in Fig. 3 where solid bars are indicative of points associated with total angles not greater than 1.8 deg and dashed error bars relate to angles in excess of 1.8 deg. No significant alteration of the variation of $Re_{\delta,t}$ with $(U/\nu)_\delta$ is suggested in Fig. 3.

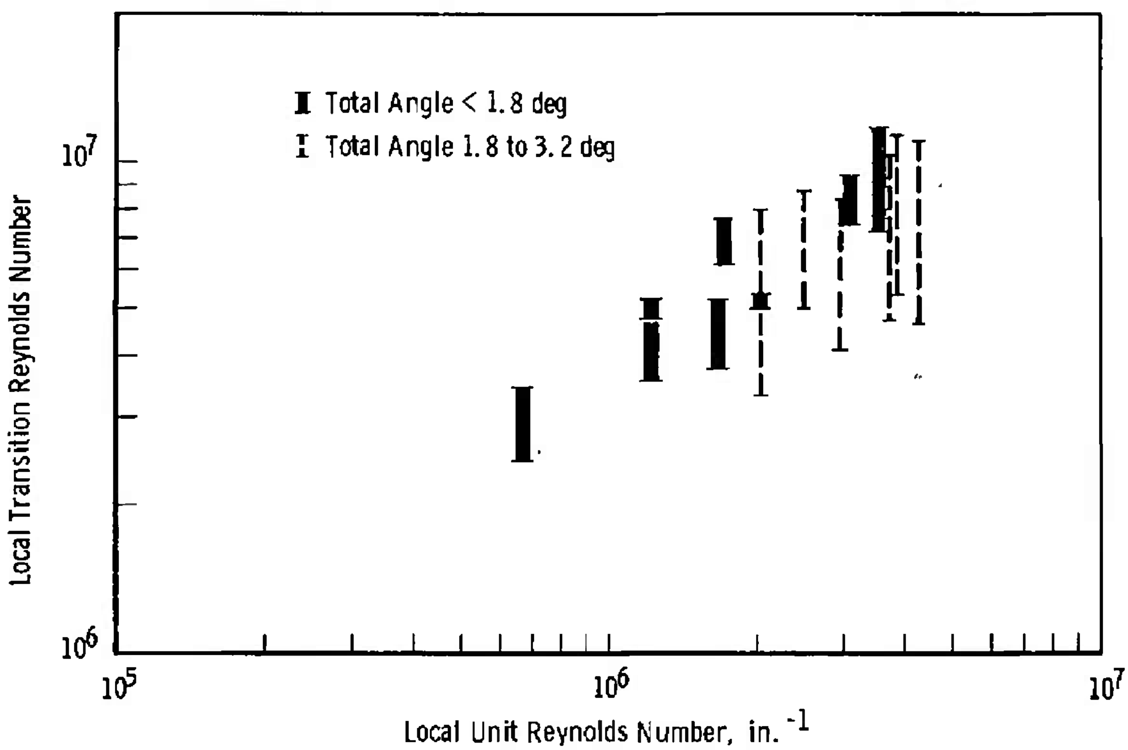

Fig. 3 Potential Influence of Angles of Attack

In Fig. 2 are shown three data points included for the evaluation of two effects that conceivably may be associated with cone nose material (1) variation in stagnation region temperature owing to differences in heating parameters between aluminum, copper, and steel, and (2) variation in nose vibration characteristics owing to differences in material properties and presence of a structural joint. It is estimated that the nose tip T_w/T_{aw} ratios varied from 0.5 for steel to 0.3 for copper, being roughly 0.4 for aluminum. Although of doubtful accuracy, these numbers should reflect the relative variation. Inspection of Fig. 2 leads to the conclusion that no effect of the nose material variation is identifiable.

Although incidental to the purpose at this time, the absolute levels of $Re_{\delta,t}$ shown in Fig. 2 may deserve comment. Perhaps most obvious is the fact that they are not markedly higher than wind tunnel results, as some might expect in view of the reduced ambient disturbances. On this point it only need be noted that our understanding of the transition process is not adequate to warrant such a judgment. In addition to the obvious differences in boundary-layer temperatures, T_w/T_{aw} ratio, M_δ, body shape, and manner of locating transition, it must be recognized that even drastic changes in free-stream disturbances may have little effect on transition if the critical frequencies are not affected or if thermal agitation is a factor, as suggested by Bechtov, Ref. 16. The tunnel data are included only to show the similarity of trends; no other comparisons are intended.

To lend further support to these observations, the drag coefficient at zero angle of attack, C_{D_o}, is plotted as a function of free-stream Reynolds number based on total wetted length, $Re_{\infty,x}$, in Fig. 4. This simply shows that the measured drag reflects satisfactory agreement with the transition locations of Fig. 2, in that using the faired curve in Fig. 2 to find $(U/\nu)_\delta$ where transition lies at the base of the 1.75-in.-diam cones yields $Re_{\infty,x}$ closely corresponding to the beginning of the transitional rise in C_{D_o} shown in Fig. 4. Incidentally, this seems to indicate that transition points, x_t, identified on shadowgrams in the present case are ahead of the fully developed turbulent boundary-layer area, as predicted earlier. It also would seem to justify the disregard of locally turbulent areas sometimes seen in the photographs upstream of the stations selected to represent x_t in this work.

Having concluded in the foregoing paragraphs that the several factors that appear most significant in regard to errors in the data did not exert enough influence to change the general result displayed in Fig. 2, the main question that motivated this investigation can be answered. Clearly the free-flight range data exhibit an effect of U/ν which is, in this case, similar to that seen in the examples of wind tunnel data shown for

comparison. The similarity in variations of $Re_{\delta,t}$ with $(U/\nu)_\delta$ in the examples shown in Fig. 2 may well be coincidental; the significant point is the readily apparent, positive slope of the range measurements of $Re_{\delta,t}$ when plotted as a function of $(U/\nu)_\delta$.

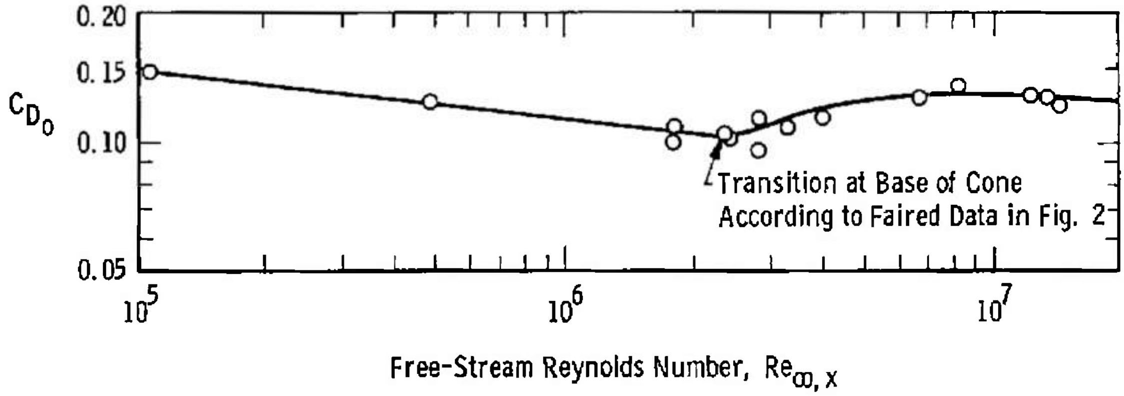

Fig. 4 Drag Coefficients Supporting Interpretation of Transition from Shadowgraphs (1.75-in.-diam Cones)

3.2 NOISE MEASUREMENT

The microphone was suspended by rubber strips in the free-flight range at the shadowgraph station. Because it was desirable to minimize any chance of hitting the microphone with an errant projectile, the microphone was positioned 26 in. (66 cm) from the range centerline and 10 in. (25 cm) from the wall. On some launches, the microphone faced the near wall; on other occasions it faced toward the range centerline. However, there was no discernible difference in signal dependent on this orientation.

To understand the manner of interpreting the sound pressure measurements in the free-flight range, it is necessary to study Fig. 5 which is a simplified sketch of the range. For simplicity, internal shielding structures are not shown. The accelerometers on the steel range tank at the plane of the parallel-light shadowgraph always began to respond at a time which was found to correspond to transmission of the sabot impact disturbance at the speed of sound in steel through the tank walls to the accelerometer location. Because this speed was significantly greater than the speed of the cone, the predominant disturbances began to spread into the range air before arrival of the cone. Both the range walls and shielding structures served to transmit these disturbances to the air. The cone arrived while the initial disturbances were propagating into its flight path, so some attention to the timing of the process was required. Further measurements revealed that the disturbances in the air reached the range centerline between 0.9 and 1.0 msec after they were indicated by the

microphone system. (If passage of disturbances at sound speed through air radially from microphone to range centerline were considered, this would be nearer 2 msec. However, there were steel microphone and schlieren window shields attached to the range walls which led to the result given.) Viewed another way, this suggested that the sound pressure corresponding to an observed transition should be that recorded from 0.9 to 1.0 msec before the arrival of the cone at the shadowgraph station. Had the cone arrived slightly earlier, any noise present would have been, in this case, indistinguishable from that reported here because of inability to sense the difference, but a 1 to 2 msec later arrival would have encountered a level of noise three to four times greater because of increased $\tilde{p}$ when the full effect of sabot impact is transmitted to the range air at the schlieren station. These points are illustrated in Fig. 6, which is a typical oscillogram.

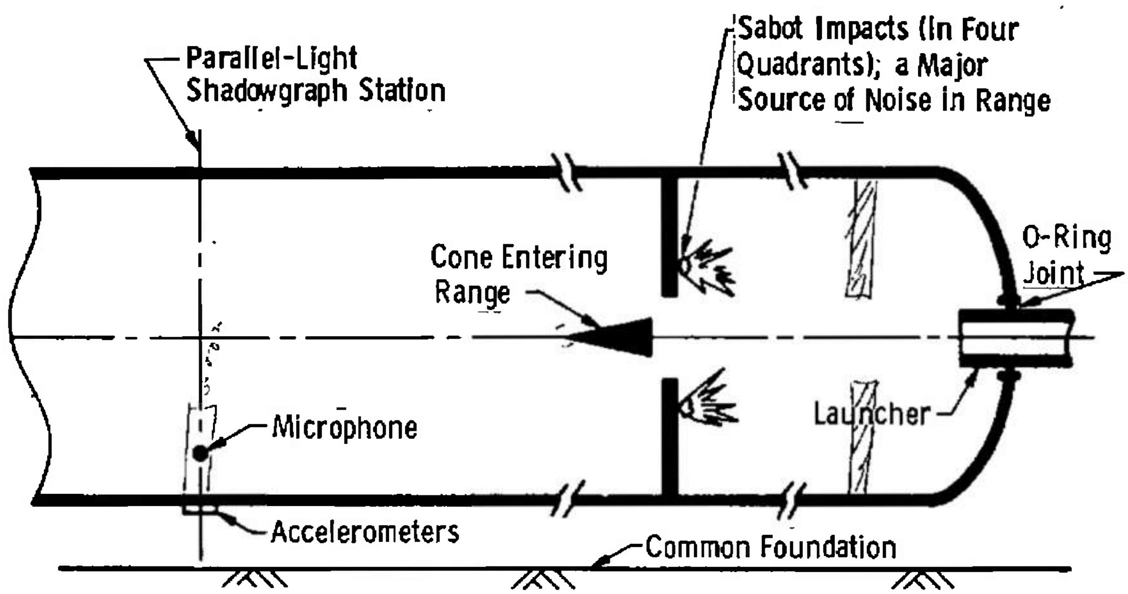

Fig. 5 Simplified Sketch of Experimental Arrangement

Root-mean-square pressure fluctuations measured, following the procedure just described, yielded an average $\tilde{p}/p_\infty \approx 10^{-5}$. Considering that lower dynamic range of the microphone system approximately corresponded to the lower sound pressures, it does not seem justified to dwell on the absolute level. Rather, the present purpose is served by comparing this order-of-magnitude result with Laufer's measurement in a wind tunnel at similar Mach number (Refs. 5 and 17). The root-mean-square pressure fluctuation ratio $\tilde{p}/p_\infty$ measured by Laufer was on the order of 0.035 with $(U/\nu)_\infty$ = 90,000 to 340,000 in.$^{-1}$ and M_∞ = 5.

(This is reduced to roughly 0. 009 if only one tunnel wall is considered.) Further, it may be noted that Pate and Schueler report $\tilde{p}/p_\infty$ varying from 0. 035 to 0. 014 as $(U/\nu)_\infty$ rises from 0. 04 x 10^6 to 1 x 10^6 in.$^{-1}$ with $M_\infty = 3$. The latter made use of a microphone system in an AEDC 40-in. continuous wind tunnel. Considering that Laufer's data in Ref. 5 show little effect of wind tunnel Mach number on the ratio $2\tilde{p}/(\gamma p_\infty M_\infty{}^2)$, it seems probable that the AEDC 40-in. tunnel and the JPL 20-in. tunnel used by Laufer have the same order of magnitude of $\tilde{p}/p_\infty$ at comparable M_∞ and $(U/\nu)_\infty$. Thus, in the present situation it is concluded that the relation characterizing typical continuous supersonic tunnels and the free-flight range case is $\tilde{p}/p_\infty$ (range) $\approx$ $\tilde{p}/p_\infty$ (tunnel) x 10^{-3}. Recalling that Laufer (Ref. 5) found that his tunnel noise was reduced by a factor of roughly 10 when he reduced U/ν enough to establish laminar boundary layers on the nozzle walls, one sees that the range environment is even more quiet than a typical tunnel with laminar wall boundary layers. In fact, even the slowly moving wake of a body in a range is exposed to less noise than in a wind tunnel, at least before the reflections of the shock waves back from the range structure into the wake region.

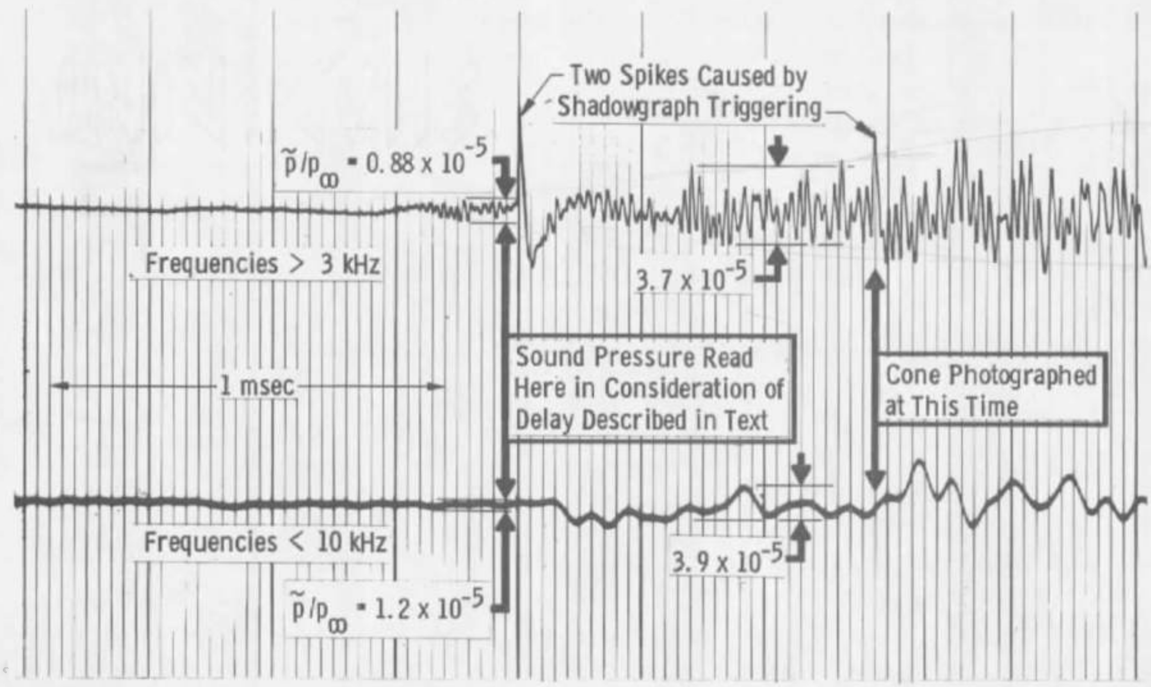

Fig. 6 Oscillogram of Shot 1621 Showing Sound Pressure Record

To conclude this account of preliminary measurements of sound pressure disturbances in a range, it is necessary to point out the roughly 100-kHz upper limit on frequency response. Although this is comparable to many older hot wire anemometer systems, like them it leaves higher frequencies of possible importance unexplored.

SECTION IV
CONCLUDING REMARKS

This investigation has established the existence of an influence of ambient pressure on the local Reynolds number at which transition occurred on sharp cones launched in a free-flight range. Under the existing conditions, i.e., $M_\delta = 4.34$, $T_w/T_{aw} = 0.18$, and $(U/\nu)_\delta = 0(10^6)$ in.$^{-1}$, $Re_{\delta,t}$ varied approximately as $p_\infty{}^n$ or $(U/\nu)_\delta{}^n$, with $n \approx 0.6$.

It would appear likely that this variation of $Re_{\delta,t}$ with p_∞ is, qualitatively at least, the same pressure or unit Reynolds number effect observed in wind tunnel data and sometimes attributed to disturbances in the flow originating from turbulent boundary layers on the test section walls. In the present case, this phenomenon was manifest under conditions of ambient air turbulence orders of magnitude less than reported for wind tunnels.

The origin of the pressure or unit Reynolds number effect is not identifiable on the basis of gross observations such as these, but it is believed that these results are significant nonetheless because they establish for the first time that the so-called U/ν effect may exist independently of the noise and free-stream turbulence associated with conventional wind tunnels.

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UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D			
(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)			
1. ORIGINATING ACTIVITY *(Corporate author)* Arnold Engineering Development Center, ARO, Inc., Operating Contractor, Arnold Air Force Station, Tennessee		2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	
		2b. GROUP N/A	
3. REPORT TITLE OBSERVATIONS ON THE INFLUENCE OF AMBIENT PRESSURE ON BOUNDARY-LAYER TRANSITION			
4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)* March 1 through October 31, 1967 - Final Report			
5. AUTHOR(S) *(First name, middle initial, last name)* J. Leith Potter, ARO, Inc.			
6. REPORT DATE March 1968		7a. TOTAL NO. OF PAGES 20	7b. NO. OF REFS 17
8a. CONTRACT OR GRANT NO. AF40(600)-1200		9a. ORIGINATOR'S REPORT NUMBER(S) AEDC-TR-68-36	
b. PROJECT NO. 8953			
c. Program Element 6240533F		9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)* N/A	
d. Task 895309			
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13. ABSTRACT

For at least 15 yr it has been known that the Reynolds number characterizing transition from laminar to turbulent boundary-layer flow (based on local properties and wetted length to transition) may be influenced by the local unit Reynolds number $(U/\nu)_\delta$ or some still unidentified, related quantity under both subsonic and supersonic conditions. Because examples of this were available almost exclusively from wind tunnel work, and because of the possibility that free-stream disturbances were responsible, there has been uncertainty as to whether the so-called unit Reynolds number effect exists in atmospheric free flight. The study described here was conducted in a free-flight range, thereby circumventing "wind tunnel effects," and it has resulted in a demonstration of the variation of transition Reynolds number with range pressure (or unit Reynolds number) under conditions of fixed Mach number and average wall temperature ratio. Some preliminary measurements of sound pressures in the range air are reported for comparison with published results for wind tunnels.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
boundary layers						
transition						
ambient pressure						
free flight						
unit Reynolds number effect						
sound pressures						